Demonstration of extreme wavefront sensing and control performance on the TPF High Contrast Imaging Testbed

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Terrestrial Planet Finder

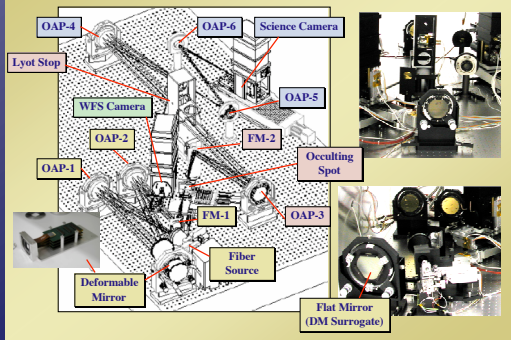
TPF

A NASA Origins Mission

Focus Diverse Phase Retrieval

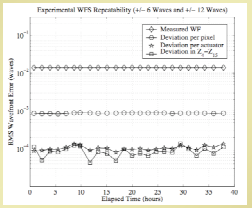
- Image based wavefront sensing (WFS) using focus-diverse phase retrieval
  - Hubble Space Telescope (HST)
    - In flight characterization of primary mirror figure and surface errors
  - Space Infrared Telescope Facility (SIRTF)
    - Used in full system ground testing leading to the accurate focusing of the secondary mirror prior to launch
  - James Webb Space Telescope (JWST)
    - Baseline methodology for finely aligning the segmented primary mirror on orbit
    - In laboratory experiments, it has a demonstrated WFS accuracy < λ/200 on small optics and a demonstrated capture range of up to 10 λ on large (>1 meter) optics
- Why it is a good choice for a TPF coronagraphic telescope
  - Its large capture range and accuracy makes it an ideal candidate for the initial alignment and correction needed after the telescope deployment
  - The science camera is used for WFS, thus no non-common path optics are employed (other than for pupil-imaging)
- Focus-diverse phase retrieval on the TPF High Contrast Imaging Testbed (HCIT)
  - It has a demonstrated experimental WFS repeatability of λ/10,000 (documented in SPIE '03 San Diego paper, results reprised here)
  - Used to control a 32x32 deformable mirror (DM) it has achieved an experimental correction of the sensed wavefront error to the λ/5,000 level (presented here)

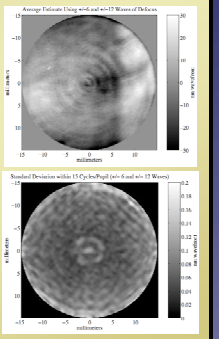
High Contrast Imaging Testbed Layout



HCIT WFS Repeatability Experiment

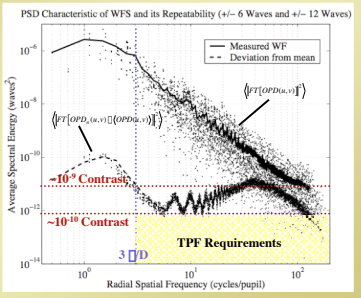
- Experiment conducted before 32x32 DM arrivals
  - Surrogate (flat) mirror inserted in its place
- Collected WFS datasets repeatedly for almost 40 hours over a couple of weekdays
  - 26 runs total (24 complete datasets)
- Vacuum tank pumped down to 10 mTorr
  - Pump was on during the experiment
- Temperature remained stable to better than 100 mC





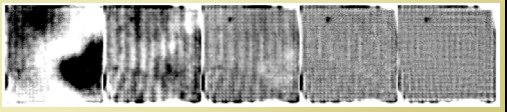
Power Spectral Density of Experimental WFS Repeatability

- The PSD of the wavefront and its repeatability are frequency distributions of energy
- Increased energy at the lower frequencies are indicative low-order mode variations
- The oscillations are related to the aberration intensity modulation of the defocused PSFs



Deformable Mirror Characterization

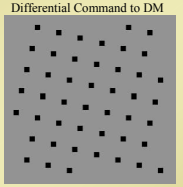
- HCIT surface gauge
  - Surface gauge is a Michelson Interferometer
    - Installed on bench in the HCIT vacuum chamber below the HCIT bench
  - In an earlier DM testing effort, it helped to achieve the control a DM to 0.25Å rms surface error
- Deformable mirror calibration and qualification for HCIT
  - Recently, two Xinetics 32x32 DMs were characterized
  - All actuators were commanded to evaluate their gains and influence functions
  - Both DMs were shown to be fully functional and capable of fully correcting themselves along with the surface gauge optical aberrations
  - The initial conservative inter-actuator command constraints prevented the full correction of a single actuator on the second 32x32 DM (see bottom figure).



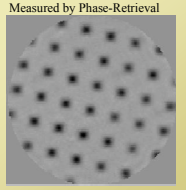
Calibration of 32x32 DM for HCIT WFC

- To enable the maximum correction of the HCIT WFE, the DM actuator mapping to the WFS coordinate system must be accurately calibrated
- We applied dilute poke patterns and observed the change in the wavefront using focus diverse phase-retrieval
- Using several such patterns, we calibrated the mapping between the HCIT WFS and the DM coordinate systems and derived the control algorithm

Differential Command to DM



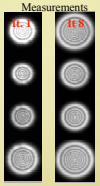
Change in HCIT Wavefront as Measured by Phase-Retrieval



HCIT Wavefront Sensing and Control

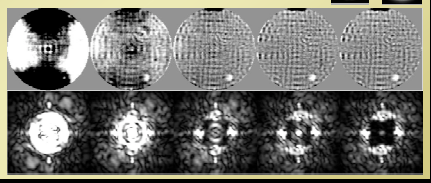
- After the DM was calibrated we conducted an iterative sequence of WFS and WFC.
- With each iteration, improved estimates of the true focus and F/# for HCIT were used to improve the defocus level selection and defocus symmetry in the subsequent focus-diverse data collection
- In this experiment, we have chosen to comply with the *conservative* inter-actuator position differential constraints. Complying with this operational rule prevents the full correction of 1 actuator within the clear aperture.

Focus-Diverse Measurements



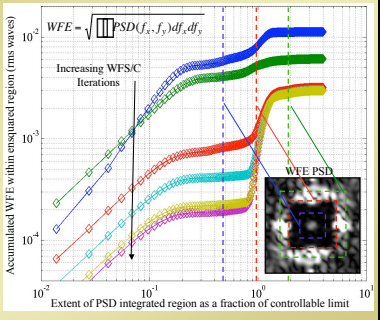
Sequence of Post- Control Wavefront Estimates

Sequence of WFE Power Spectral Densities



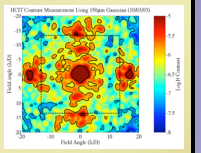
Analysis of WFS/C Performance

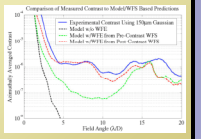
- The set of curves depicts the state of the WFE on HCIT over the iterations of WFS/C.
- Each curve represents the accumulated WFE as a function of the size of the ensquared region within the PSD of the wavefront error.
- The WFS/C process achieved a correction of HCIT WFE to about the λ/5000 level within the controllable passband
- Beyond this Nyquist limit for the DM, the WFE is a combination of the uncontrollable WFE within HCIT and the DM print-through.



Initial Contrast Results

- Post-WFC high contrast imaging performance
  - After the last WFS/C iteration, we aligned the coronagraph and measured the system contrast
  - The contrast produced by the corrected system was about 10^{-9} or better over a large portion of the controllable field.
    - This is inconsistent with the wavefront quality implied by the last iteration of WFS/C
  - WFS that was conducted after the coronagraph run indicated that the HCIT wavefront error had increased by 2nm rms
    - This drift in the wavefront was correlated with temperature variation observed during the experiment
    - This wavefront measurement is consistent with the measurement of the system contrast (See plot)
- Ongoing activities on HCIT
  - Improving HCIT thermal stability
    - The temperature set-point of the chamber has been increased to improve overall stability
    - The DM thermal control system is now active
  - Improving the cycle time to measure contrast
    - This was the first run with the DM and several degrees of freedom had to be aligned within the coronagraph. (4 hours had elapsed)
    - In addition to the Xenon arc-lamp, we are in the process of installing a laser source to reduce our integration times





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